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REINFORCED CONCRETE CHIMNEYS

BULLETIN No. 18



PUBLISHED BY THE

ASSOCIATION OF AMERICAN PORTLAND
CEMENT MANUFACTURERS

BELLEVUE COURT BUILDING, PHILADELPHIA

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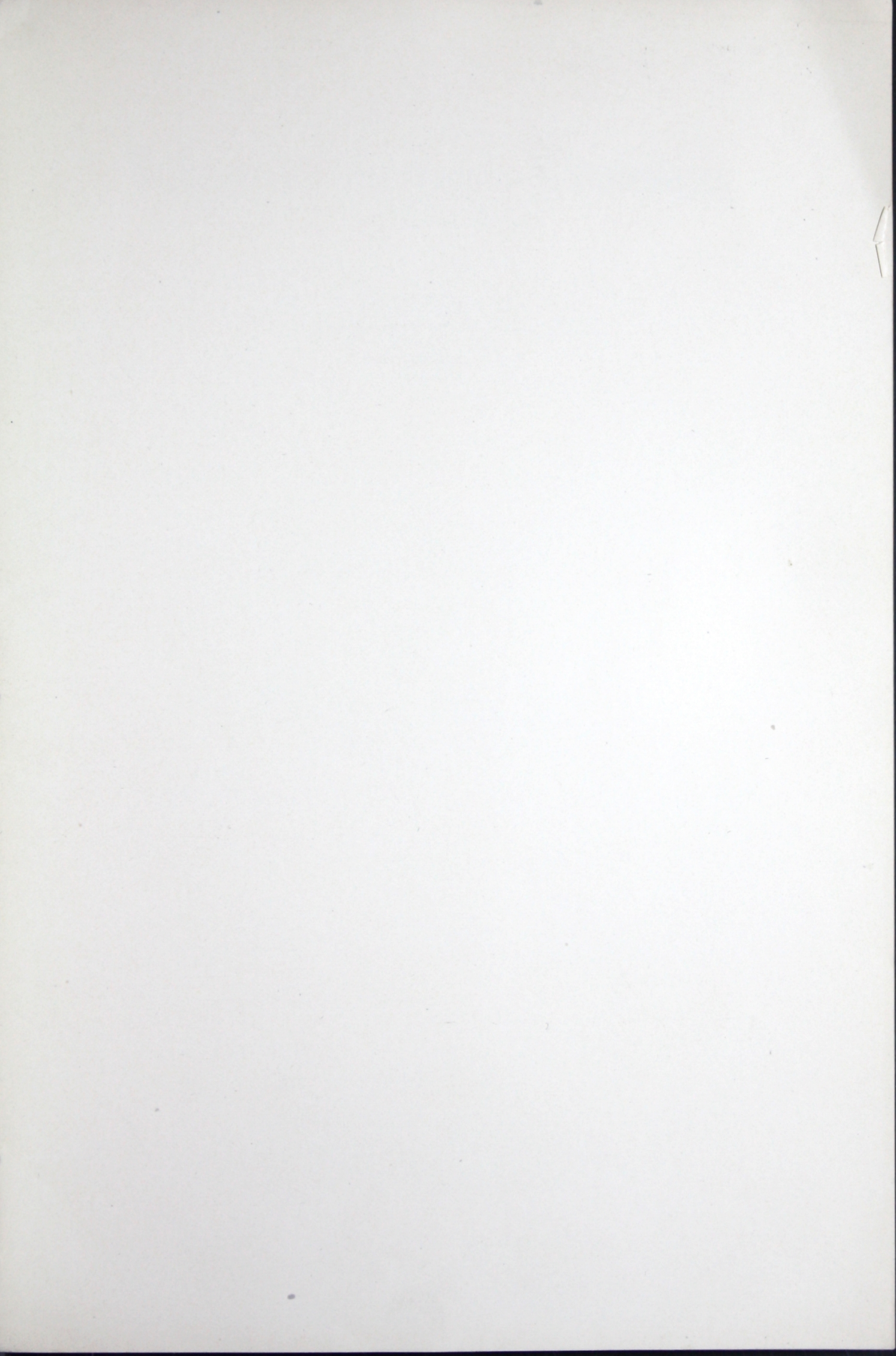
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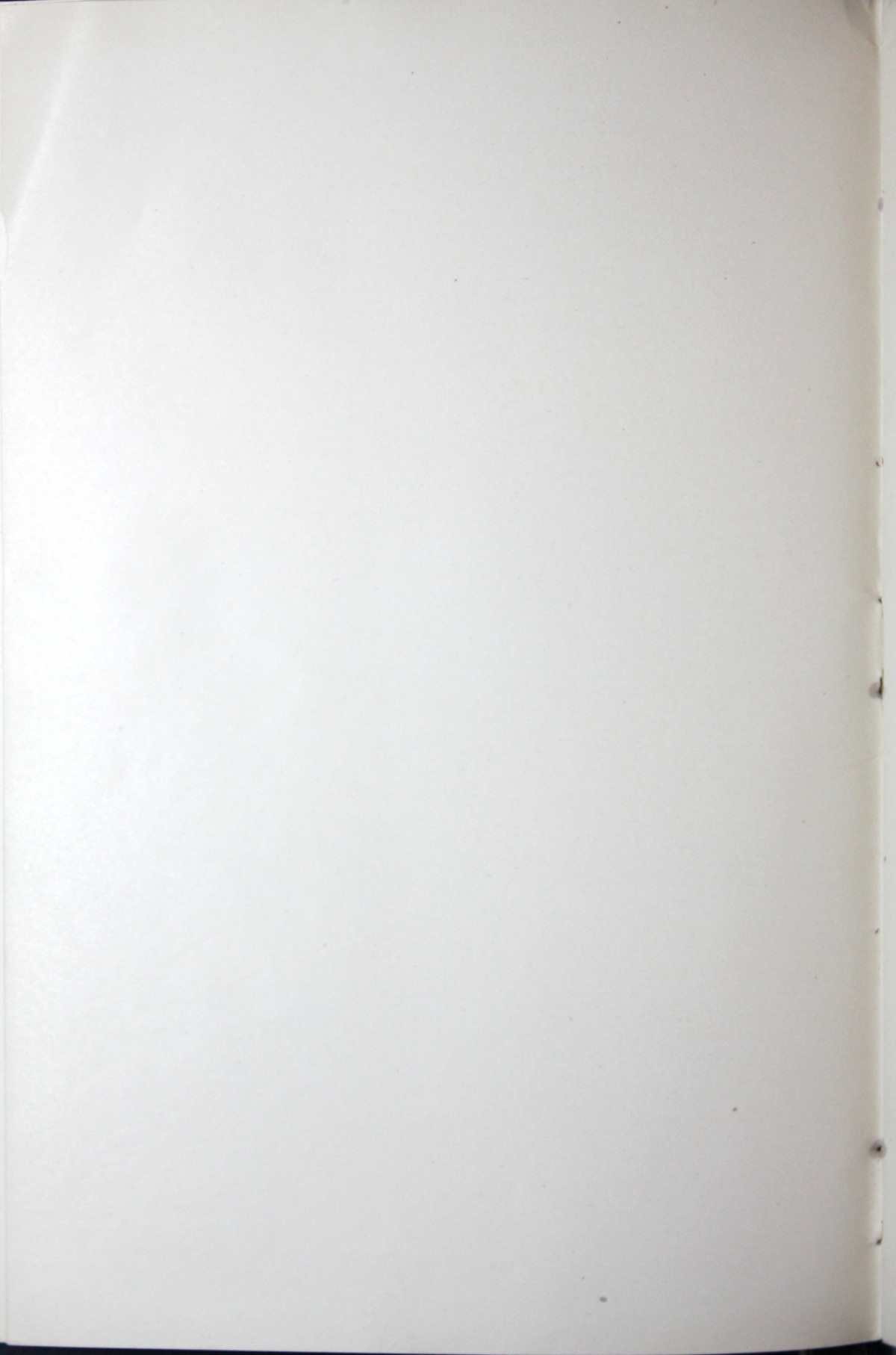
HOULD you find this bulletin helpful in building with concrete, we would consider it a favor to have you so inform us. Likewise, we would appreciate a description (and a photograph, if possible) of what you have built. In this way you will assist us in aiding others in the same way we trust we have helped you.

If you do not fully understand any part of this book, or if you desire further information, we would be glad to have you write to the

ASSOCIATION OF
AMERICAN PORTLAND CEMENT MANUFACTURERS

BELLEVUE COURT BUILDING, PHILADELPHIA, PA.





Reinforced Concrete Chimneys

(Bulletin No. 18)

Report of Investigation made for the
Association of American Portland Cement
Manufacturers

By

Sanford E. Thompson

M. Am. Soc. C. E.

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Report of Investigation made for the Association of
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SANFORD E. THOMPSON*

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The first reinforced concrete chimney was built in 1898 by the Ransome & Smith Company for the Pacific Coast Borax Company, Bayonne, N. J. Since that time about 400 stacks have been completed, and are distributed through nearly every State of the Union and Canada. These stacks range in height above ground from 50 to 352½ feet with inside diameter ranging from 4 to 18 feet, the majority of them being 150 to 200 feet high and 5 to 6 feet inside diameter.

Although the large majority of these chimneys have given satisfaction to their owners up to the present time, the failure of a few and serious cracks in several others have caused a number of inquiries to be made as to the reliability of reinforced concrete for chimney construction.

As a consequence of such questions your Association has delegated the writer to investigate the causes of the faulty structures, and the condition of the chimneys now in service, with a view to reporting whether reinforced concrete may be safely recommended for chimney construction.

With this object the writer has visited and carefully examined a number of concrete chimneys; has investigated the causes for the defects in these structures; and has consulted the representatives of some of the companies which make a specialty of this type of construction. Through inquiries made by your Association and by personal correspondence direct reports have been received upon 150 chimneys.

The results of this special investigation taken also in connection with two or three professional cases, in one of which opportunity was afforded for examination of the material in a chimney which was being taken down, provide data for this report.

*Consulting Engineer, Newton Highlands, Mass.

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CONCLUSIONS.

It is thus possible to present quite definite conclusions and recommendations with reference to this class of construction. The general conclusions which follow will be considered in detail in subsequent portions of the report and reasons will be given for their adoption.

(1) Reinforced concrete is a suitable material for chimney construction.

(2) Reinforced chimneys must be designed and built upon the same principles and by the same methods which have proved essential in other types of reinforced concrete construction.

(3) The defects and failures which have occurred in chimneys thus far built have been due to poor workmanship, faulty design or the use of the wrong concrete mixtures or to all three.

(4) The methods of construction at present being followed in many cases are defective and likely to lead to subsequent failures and they should be radically modified.

TYPES OF CONCRETE CHIMNEYS.

One of the tallest chimneys in the United States is of concrete construction and located at Butte, Mont., at the mines of the Colusa Parrot Mining & Smelting Company. This chimney, which was built in 1905, is illustrated in Fig. 1, and the method of erection with the forms in place is shown in Fig. 2. The stack is $352\frac{1}{2}$ feet high above the ground, and its inside diameter 18 feet. The walls of the lower 21 feet of the chimney are 18 inches thick and above this is the double shell, the outer shell being 9 inches and the inner 5 inches thick with a 4-inch air space between them. The inner shell extends to a height of 101 feet above the base. The vertical reinforcement is $1\frac{1}{4}$ inch by $1\frac{1}{4}$ inch by $1\frac{1}{4}$ inch T-bars and the horizontal reinforcement, of 1 inch by 1 inch T-bars, varies in spacing from 12 inches to 3 feet apart. Mortar of proportions 1:3 was used in the construction. The builders were the Weber Steel-Concrete Chimney Company.

The foundation of the chimney is unusual, consisting of a base 18 feet in depth, formed of molten slag in which steel wire rope, chain and T-rail are imbedded, and upon which is

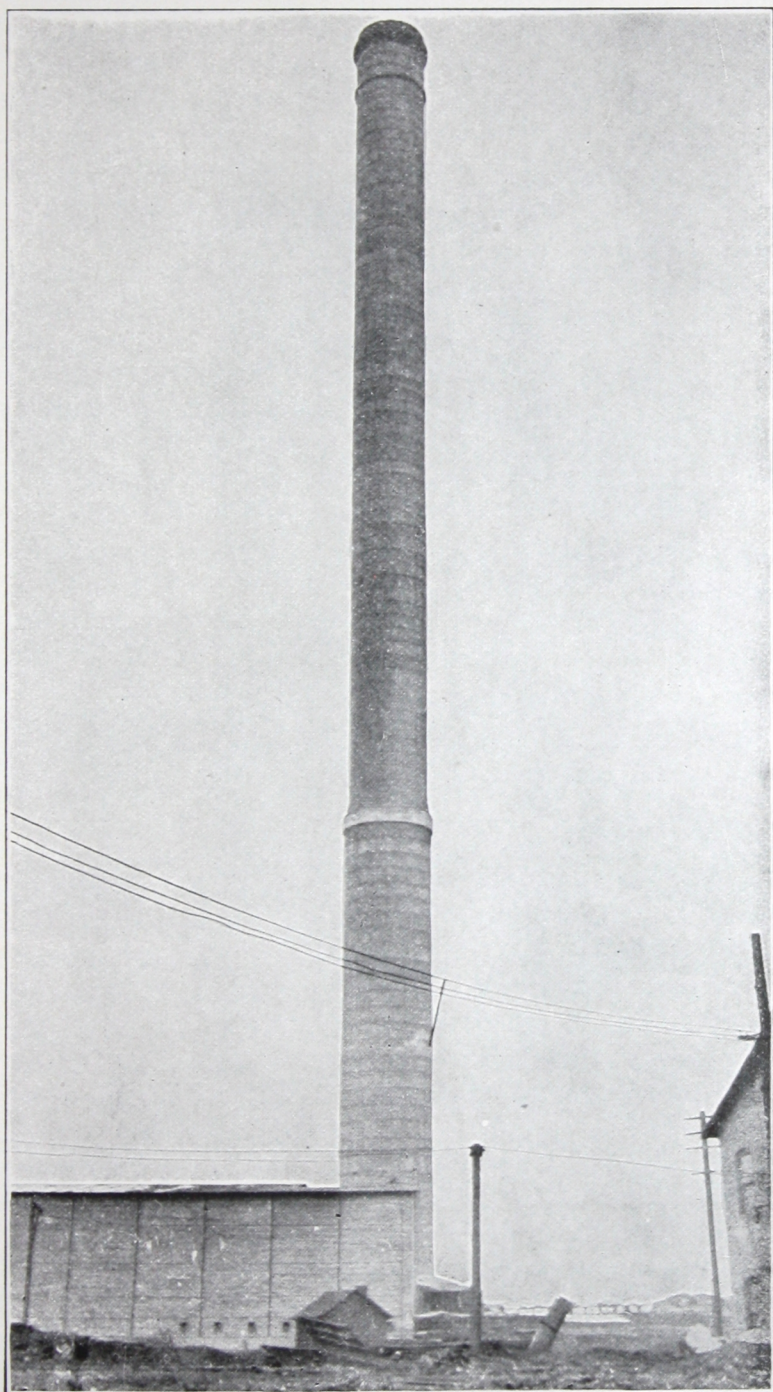


FIG. 1. CHIMNEY OF THE BUTTE REDUCTION WORKS OF MONTANA
(See page 4)

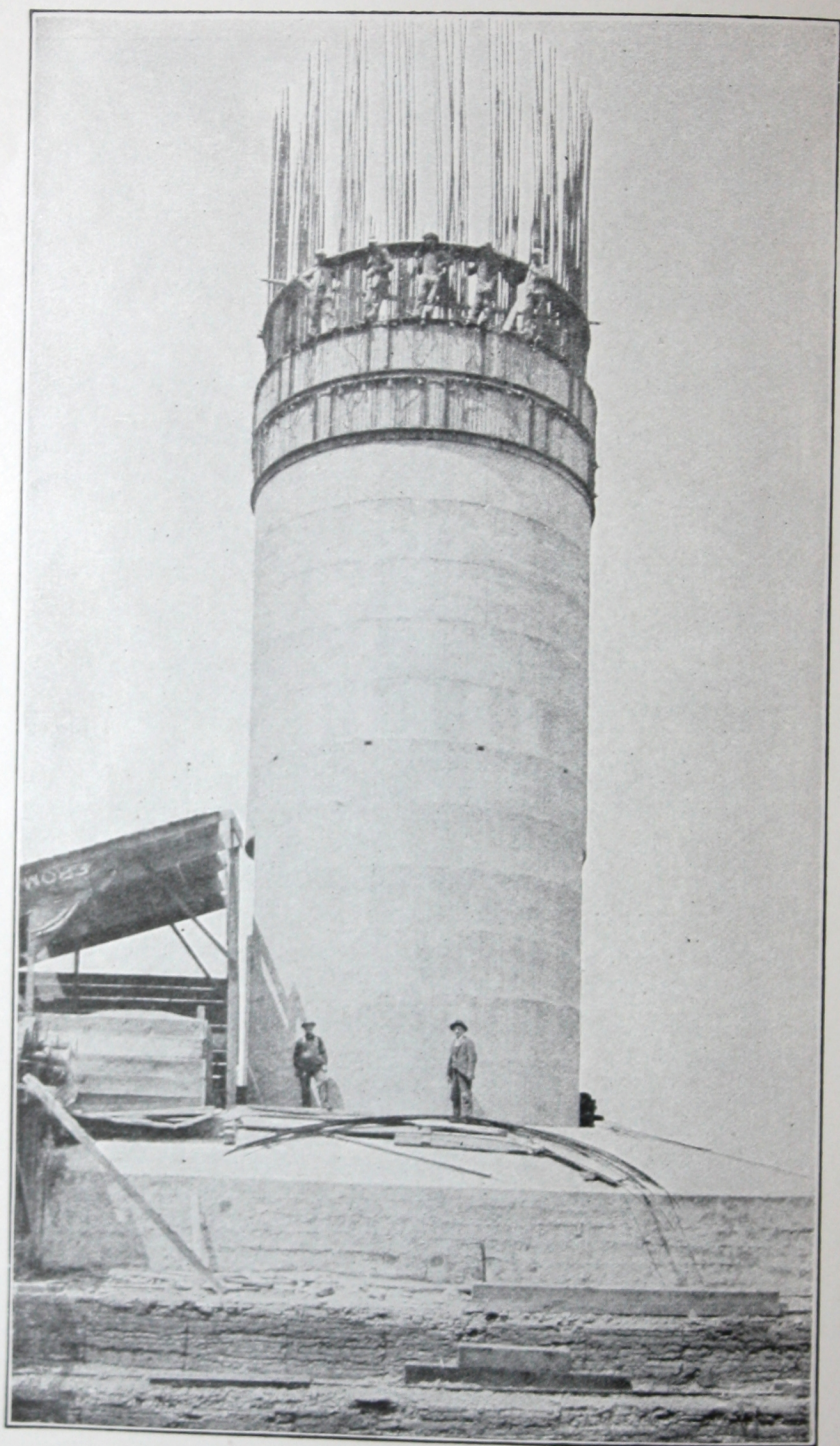


FIG. 2. BUTTE CHIMNEY IN COURSE OF ERECTION
(See page 4)

placed the reinforced concrete footing for the chimney proper.

The chimney of the Pacific Electric Railway Company at Los Angeles, Calif., illustrated in Fig. 3, was built on the Ransome System in 1902. The lining, as shown, extends the entire height of the stack, and both the interior and exterior shells are reinforced with twisted steel rods.

The chimney at Bayonne, N. J., already mentioned, is of a similar type of construction, 150 feet high by 7 feet inside diameter. The concrete was composed of cement, sand and broken stone.

As an illustration of the rigidity of a concrete chimney, a stack built in 1901 in Jersey City may be instanced. Owing to defects in the pile foundation it is out of plumb about 20 inches, and yet it stands firm, and unless the foundation yields further, is entirely safe.

A chimney of uniform outside diameter from bottom to top is illustrated in Fig. 4. This was designed and built by the Alphons Custodis Chimney Construction Company for the Edison Electric Illuminating Company, in Brooklyn, N. Y., and the design is shown in Fig. 5. The vertical rods are of round steel $\frac{3}{4}$ -inch in diameter, and the horizontal rods of $\frac{1}{2}$ -inch steel.

Metal forms were used in the construction, of the type shown in Fig. 6.

The chimney of the Mobile Electric Company, 175 feet high by 11 feet inside diameter, is illustrated in course of construction by the American Chimney Company in Fig. 7.

In this type of chimney the inner shell, which extends to the offset shown, is connected with the outer shell by a flexible diaphragm and below it are holes extending through the wall for the ventilation of the air space. T-bars were used in the construction of this chimney, with 1:3 mortar.

A tapering chimney is illustrated in Fig. 8. This is erected at Williamsport, Md., being built for W. D. Byron & Sons by the Concrete Construction Company with Mason D. Pratt as Consulting Engineer. The chimney is 120 feet high with an interior diameter at the base of 5 feet 6 inches. The vertical reinforcement is $\frac{3}{4}$ -inch round steel, with occasional circles of horizontal rods $\frac{5}{8}$ -inch diameter. The lining, which extends to a height of 35 feet, is of firebrick.

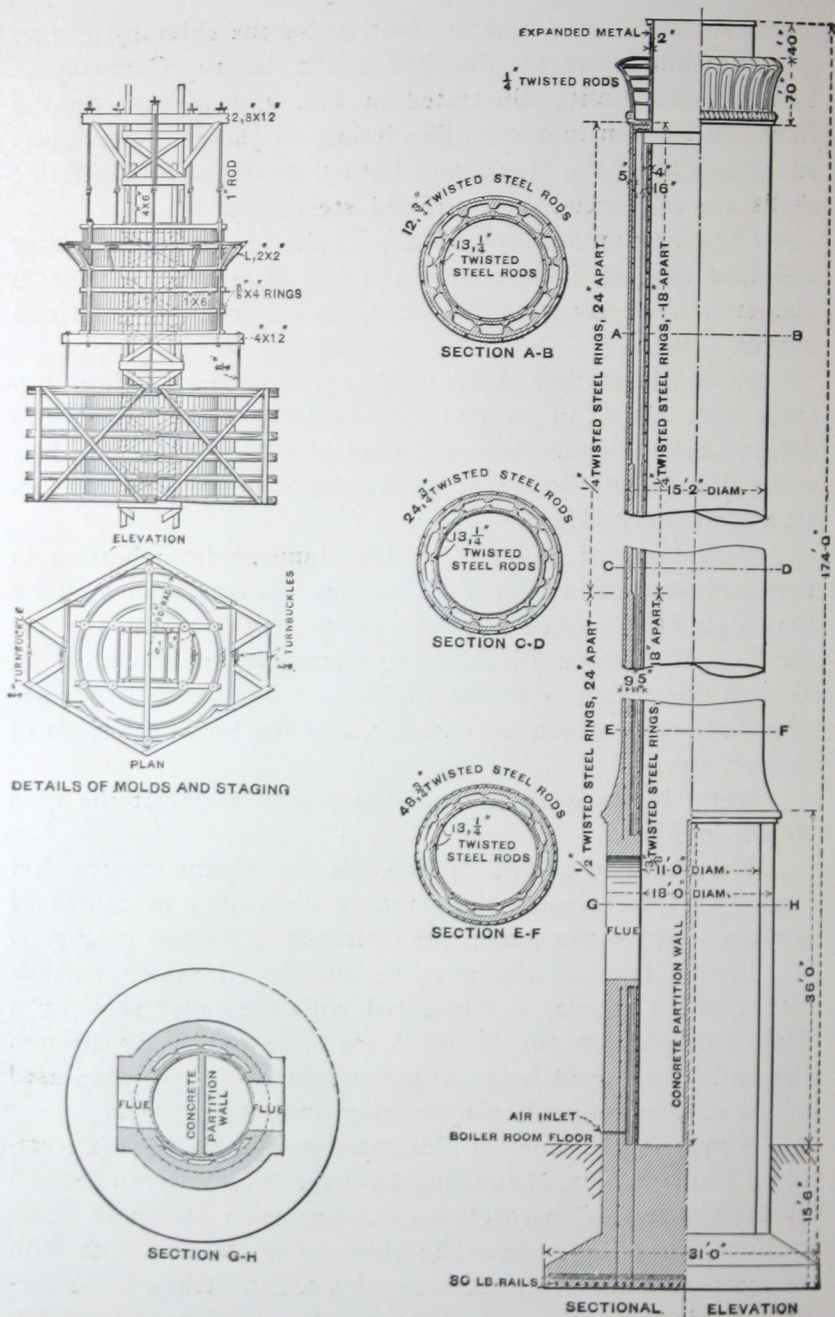


FIG. 3. CHIMNEY OF PACIFIC ELECTRIC RAILWAY POWER HOUSE,
LOS ANGELES, CALIFORNIA
(Reproduced by permission from Taylor and Thompson's "Concrete, Plain and Reinforced")

(See page 7)

The construction of the forms is illustrated in the photograph, Fig. 9. These are made in eight sections and are bound by steel wire so that by changing one tapering board in each section, the necessary batter is produced.

The chimney of the Peoria Stone & Marble Works Co., at Peoria, Ill., is shown in Fig. 10. The stack, which is 150 feet high by 5 feet inside diameter, is built by laying up fire clay tiles of H-shape, which are filled with concrete and reinforced with steel rods vertically and horizontally. There is no inner shell. The design of the stack is given in Fig. 11.

A somewhat similar type of construction to that last shown is the chimney of the Salem Laundry Company at Salem, Mass. This, as illustrated in Fig. 12, is constructed of hollow concrete blocks, filled with wet concrete as they were placed, and reinforced with vertical and horizontal steel. There is no inner shell but the interior is lined with asbestos to a height of 17 feet.

A chimney built by Ballinger and Perrot, in the interior and as a part of a ten story building in Pittsburgh, Penn., is illustrated in Fig. 13. Only the top of the chimney appears above the roof.

The Metal Concrete Chimney Company pack the joint at the top of the inner shell with asbestos. They also employ a slight modification of the usual form of construction by hooking the ends of the reinforcing rods.

INVESTIGATION OF CHIMNEYS.

As already intimated, several reinforced concrete chimneys have fallen while being constructed or at some later period, and the cracks developed in a number of others have raised serious question as to their safety. On the other hand, in general, chimneys built of reinforced concrete have given perfect satisfaction, this being attested by the fact that the owners have repeated their orders for such stacks, one corporation, for example, having built fourteen of them at its plants in various parts of the country.

The question then which confronts us is whether the faulty structures reported are due to qualities inherent in reinforced concrete; or whether they are due to defects in design and methods or construction which may be amended

in the future; or whether they may be considered simply as accidental failures to which all engineering structures are occasionally liable. In other words, shall we condemn the building of chimneys of reinforced concrete, or may we disregard the comparatively few actual failures as accidental, or shall we approve of building concrete chimneys, at the same time insisting that, to be sure of permanence, the methods of design and construction must be in some cases radically changed?

My investigations and examinations of chimneys have led me very decidedly to the third alternative. In other words, the writer is convinced that reinforced concrete chimneys can be built which are entirely safe and practically indestructible, while recognizing that many have been erected with an utter disregard of the fundamental principles which have proved essential in all other classes of reinforced concrete construction.

In the first place, as we consider the problem, two principles must be recognized which may be termed axioms in engineering science. Namely, failures do not necessarily throw doubt upon any class of construction unless the causes for failure are incapable of remedy. On the other hand, the fact that one structure or many structures have not failed is no proof that they are properly designed and built, since they may not have met with the most severe conditions or may be already stressed to a point so near breaking as to be liable to future deterioration from heat and frost and continued vibration.

In reviewing the subject, therefore, the examination must be especially directed to the causes of the occasional failures and defects reported, with the object of determining if possible whether the conditions which have produced the troubles may be present in other chimneys and how they may be corrected in the future to prevent recurrence.

Eight chimneys have been reported which have either blown over or have been taken down because they were defective, and ten or twelve others have been heard from in which cracks have developed which cause serious apprehension. In nearly every case of failure the chimney has been rebuilt by the construction company.

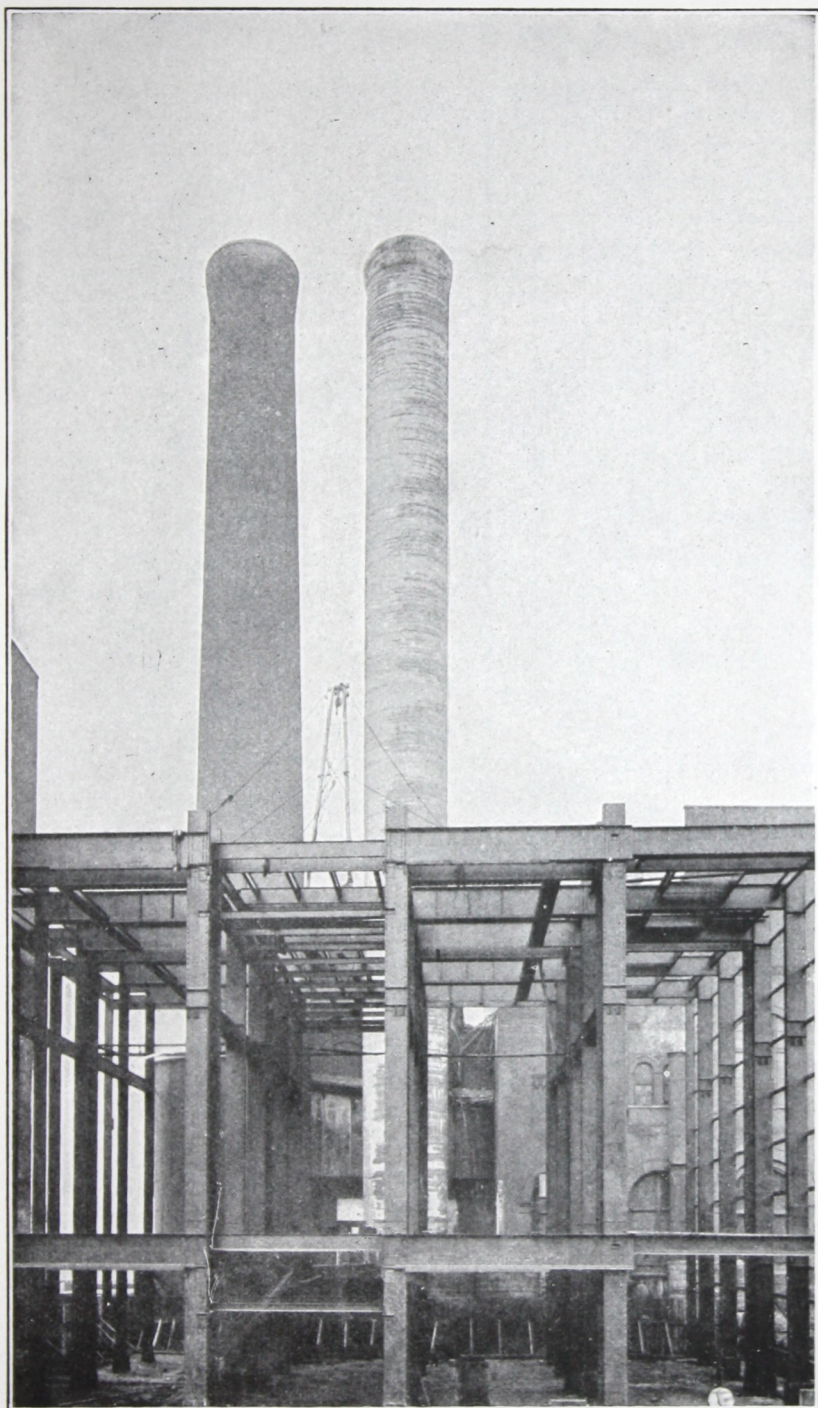
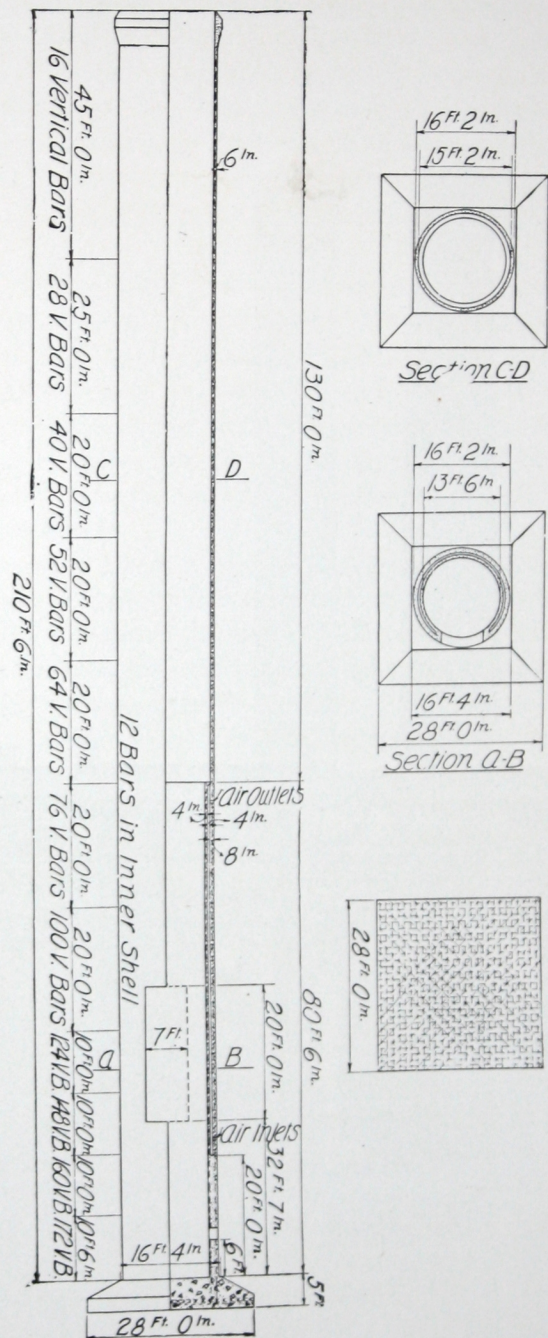


FIG. 4. CHIMNEY OF THE EDISON ELECTRIC ILLUMINATING CO., BROOKLYN, N. Y.

(See page 7)



One of the failures most widely known is that which occurred at Peoria, Ill., in 1906. The chimney had been completed about three weeks when it gave way at the offset or projection, the upper part crumbling as it came down, and the concrete breaking into small chunks. The T-shaped steel stripped clean from the concrete. The cause is stated to be a poor batch of concrete at the offset, although the manner of failure would indicate that the concrete in the upper portion also was not of the best quality.

Another case is cited in which the chimney stood for nearly two years, and then blew over in a wind storm of about forty-five miles per hour. Here, as in the other cases, the concrete stripped from the steel, and the fall was attributed to poor adhesion between the concrete and steel.

A stack built in very cold weather in Canada blew over when the concrete, which evidently froze without setting, thawed out.

A case occurred in 1905 in which the upper 30 feet broke and slid down while it was being topped off, the accident being charged to the fact that the mortar had not properly set.

This year a chimney in the West after about two years' service developed such cracks that it was considered dangerous, and was taken down and replaced.

Another stack was torn down before the boilers were fired because of defects in the workmanship.

The most recent failure occurred this last summer in Wisconsin where a chimney blew over only two weeks after its completion in a severe tornado which damaged many other structures. The blame is laid upon the unusual severity of the storm and the freshness of the concrete.

Considering the chimneys which are now in commission, we find that in general they are subject to more or less checking or cracking. This need not necessarily condemn the structure since the reinforcement may be sufficient to safely hold together the blocks formed by the cracks, and yet it would seem with the opportunity we have of introducing steel wherever needed that all cracking ought to be averted, especially as there is always danger that the cracks may increase from wind vibration, heat and frost.

Most of the reports indicate that the cracks are not con-

sidered dangerous by the owners of the stacks. In several instances, however, long vertical cracks have appeared, and in others horizontal cracks have been found in the lower portion which have given serious concern. One chimney, straight when built, has since leaned 3 to 4 inches from the vertical, beginning at a point about two-thirds way from the base. Another informant reports soft spots in his chimney.

Photographs of a portion of a chimney which has developed cracks of a somewhat serious character are shown in Figs. 14 and 15, pages 33 and 34.

The pictures clearly show the 3-foot section constituting a day's work, and also by the wavy lines, approximately horizontal, the joints between the 6-inch layers in which the concrete was placed. The irregular line just below the offset represents a horizontal crack extending all around the chimney, and there is a continuous crack at the second horizontal section joint below this, as well as a number of vertical cracks through the offset, at least one of these extending clear to the top of the stack.

Nearly 400 reinforced concrete chimneys have been built in this country, and direct reports have been received by your Association and by the writer from nearly half of them. The failures cited amount to about 2% of the total number with at least 2% to 3% more of doubtful safety. It is probable that most of the seriously defective cases have been brought to light since special care has been expended in running down doubtful ones. Of the others and even where personal examination has revealed somewhat serious cracks, the general verdict of the users is "satisfactory" and "good."

Reinforced concrete chimneys offer special structural difficulty, because of the heights to which they are carried, and the accompanying difficulty of obtaining the very best of workmanship. For this reason we might expect a somewhat higher percentage of error than in ordinary reinforced concrete construction. Even taking this into consideration, however, 4% appears to be a somewhat alarming percentage of defective construction. But the vital question is whether even these few cases may be passed over as isolated cases of defective construction, or whether they afford an arraignment of other chimneys now standing; and whether they predicate a similar percentage of defective construction in the future.

An examination by the writer of a chimney which was taken down, if representative of others, throws considerable doubt upon their durability. On the other hand, it affords means for pointing out definitely the errors which must be

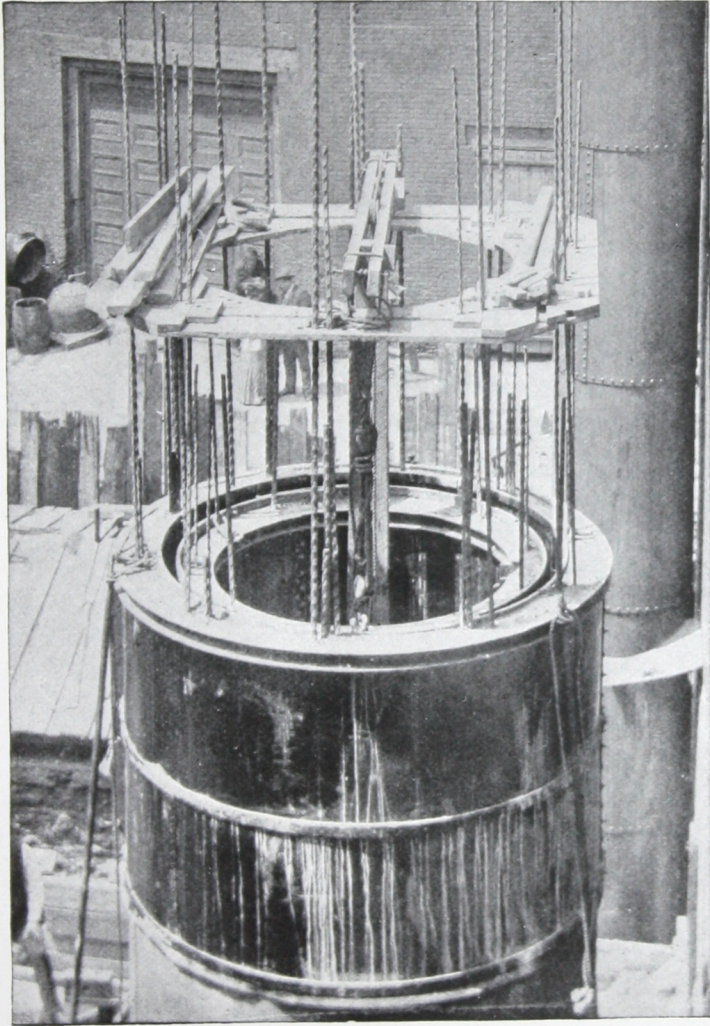


FIG. 6. METAL FORMS FOR CHIMNEY CONSTRUCTION
(See page 7)

guarded against in the future. This chimney showed soft spots in three of the sections, where the concrete could be readily loosened clear in to the steel. The concrete was porous

throughout, and scarcely bonded between the 6-inch layers. Samples cut from good portions of the concrete, which was a mortar, one part cement to 3 parts sand, gave an ultimate strength of about 1200 pounds per square inch or about one-half the strength of a good 1:3 mortar laid with a sufficient quantity of water. A month after this inspection the chimney was taken down, the 6-inch layers being readily loosened from each other and cut in pieces by a pneumatic chisel, and the concrete was found to vary materially in hardness. Of special importance was the fact that the mortar in the angles of the T-bars was weak and porous, showing scarcely any adhesion to the steel. Inquiry showed that the concrete or mortar used in the construction was of **such extremely dry consistency** that even where well rammed, the moisture did not cover all parts of the surface of a layer nor did it produce a proper bond with the steel.

From such evidence it is impossible to avoid the conclusion that other chimneys built by similar methods, with so dry a mixture as to give a weak, porous concrete and to provide insufficient adhesion to the steel, are likely to cause trouble in the future.

This appears to be a severe arraignment of concrete chimney construction. And yet to be fair, it must not be overlooked for a moment that every one of the points brought out,—the low strength of the concrete, the dry mix, the porosity, the lack of adhesion to steel, the lack of bond, and the soft spots,—indicate construction which would not be tolerated in any other class of reinforced concrete work. It has been proved beyond a doubt, and reiterated in print and verbally, that reinforced concrete must be mixed **wet** in order to adhere to the steel and protect it from corrosion; that a factor of safety of 4 is certainly a minimum in compression; and that a concrete structure must be essentially monolithic. It should be clearly understood also that in the chimney to which I have just referred all of these essential elements were disregarded.

The defects noted are not inherent in chimney construction. In other words, from a practical standpoint it is not only possible but absolutely necessary to follow in chimney construction the methods which have been proved necessary

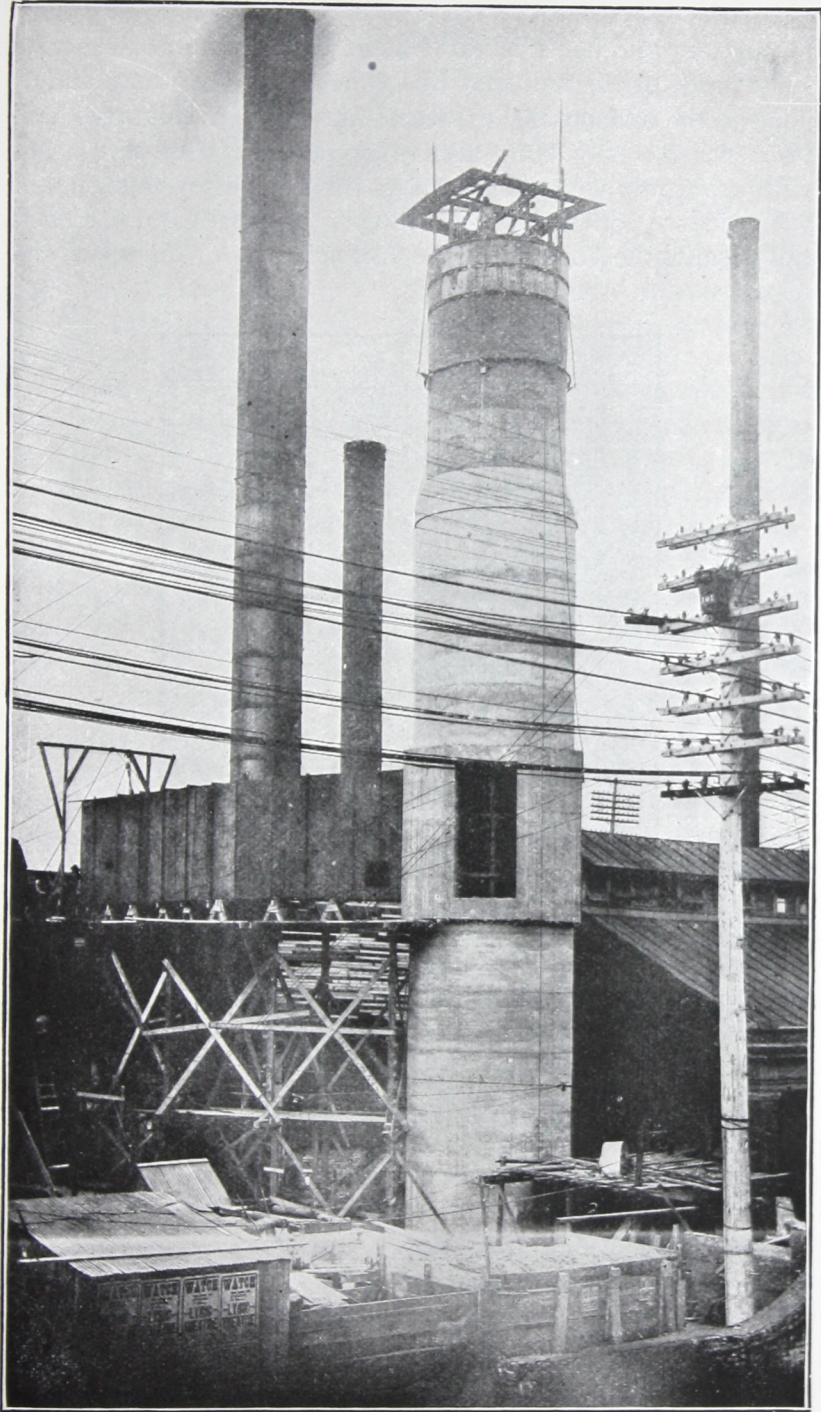


FIG. 7. CHIMNEY OF THE MOBILE ELECTRIC CO., MOBILE, ALA., UNDER CONSTRUCTION

(See page 7)

for success in other structures made from reinforced concrete. As a proof of the fact that this can be done, we may simply point to the indisputable evidence that concrete chimneys have been satisfactorily built with a proper factor of safety and with a wet mix which insures a positive bond to the steel, and with a dense concrete which protects the steel from corrosion and permits the bonding of the various parts of the structure.

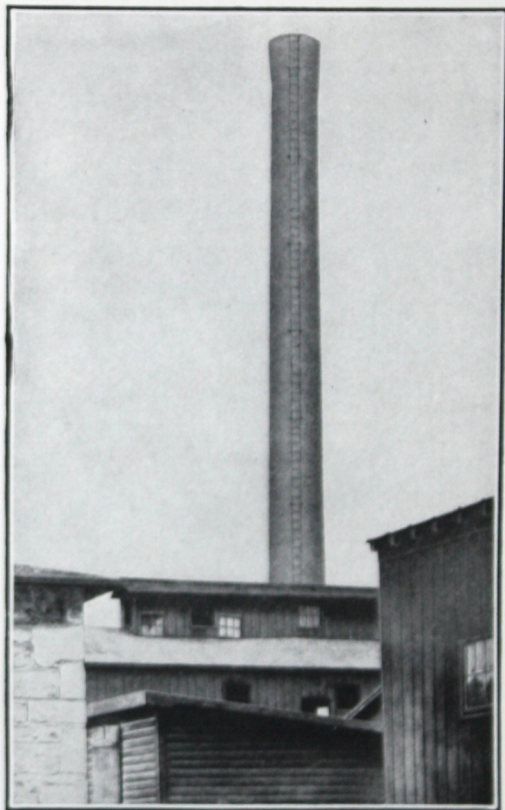


FIG. 8. CHIMNEY OF W. D. BYRON & SONS AT WILLIAMSPORT, MD.
(See page 7)

Since reinforced concrete is everywhere being constructed on these principles, and is proving durable and satisfactory, and is being used under all conceivable conditions, we have ample cause for security in reinforced concrete chimneys provided they are properly designed and constructed.

EFFECT OF HEAT UPON THE CHIMNEY.

In the above discussion the effect upon the chimney of the interior heat from the boilers is not directly referred to. Just what part this has played in the faults which we have noted is uncertain. Undoubtedly the interior heat adds to the stress in the concrete, and thereby increases the tendency to crack especially at points near the top of the inner lining. This simply indicates, however, that the quantity and arrangement of the steel reinforcement should be adapted to resist this extra stress.

When reinforced concrete was first introduced it was questioned whether with changes in temperature the concrete and the steel would not expand and contract unequally, so as to make them separate from each other. If this were the case, it would be especially detrimental to a structure like a chimney where the range in temperature is greater than usual. It has been proved conclusively, however, that concrete and steel have substantially the same coefficient of expansion, that is, with any degree of heat they expand and contract almost exactly alike. For this reason there can be no separation due to change in temperature.

The interior heat affects the shell in another way because concrete is a poor conductor. The interior surface for a depth of an inch or two is heated very much hotter than the exterior surface, and so tends to expand and crack the colder outside surface. This effect is most marked upon a thick wall, the action being similar to that of a thick glass bottle which breaks more readily when hot water is poured into it than does one of thin glass. The stress or pull on the outside surface must be met by increasing the amount of circular steel and placing it near to this outside surface.

The effect of heat upon the concrete material itself is also a point which must be considered in chimney design. In the earliest chimneys built the concrete lining extended the full height while in later ones it has been generally carried up to only about one-third of the height. Usually the lining has been reinforced concrete, although in some cases firebrick has been used. A few chimneys have been built with no lining at all.

While much remains to be learned with reference to the

effect of heat upon concrete, it is known to be a most excellent fire-resisting material, although it has been found that a temperature as high as 1500° Fahr. continued for only two or three hours will draw out the water of crystallization so as to take away the strength for a depth of $\frac{1}{2}$ to 1 inch. Lower temperatures affect the material less, and tests at the Watertown Arsenal indicate that a good cement mortar will not be appreciably injured at 600° to 700° Fahr. Tests of actual chimney temperature are extremely meagre, but from records available we may say that the temperature in an ordinary chimney seldom exceeds 700° Fahr. at the base, while 400° to 500° is more usual. It is a fact not universally known among engineers that the temperature in a chimney remains quite high even in its upper portion. For example, in the test of one chimney the temperature at three-quarters of the height above the base ranged only 10% to 20% lower than at the flue. This makes it evident that if the lining extends only one-third of the way from the bottom, the design of the concrete shell above it should be adapted to resist considerable heat, while greater safety may be insured by extending the lining far above the lower third.

Your Association has received no reports of injured linings. Many have never examined the interiors of their chimneys but several have reported that the lining was in good condition. One correspondent states that after three months' use the interior surface of the chimney is smooth, without cracks, and that the soot does not adhere to the surface but falls to the bottom or is carried out by the draft. Since the fire-resisting quality of concrete increases very greatly with age, it is fair to assume that if the interior surface is sound at the end of the first two or three months, it will not disintegrate after that time. Right in this connection Mr. E. L. Ransome reports a recent examination of the inner shell of a chimney built nearly ten years ago of a true concrete of cement, sand and broken stone, in which he found the concrete in the hottest part of the chimney opposite the flue perfectly sound and exceptionally hard.

Concrete then may be considered as satisfactory for a lining or an inner shell in ordinary cases, although when exceptionally high temperatures are expected, say, above 750° Fahr., it is on the side of safety to employ firebrick.

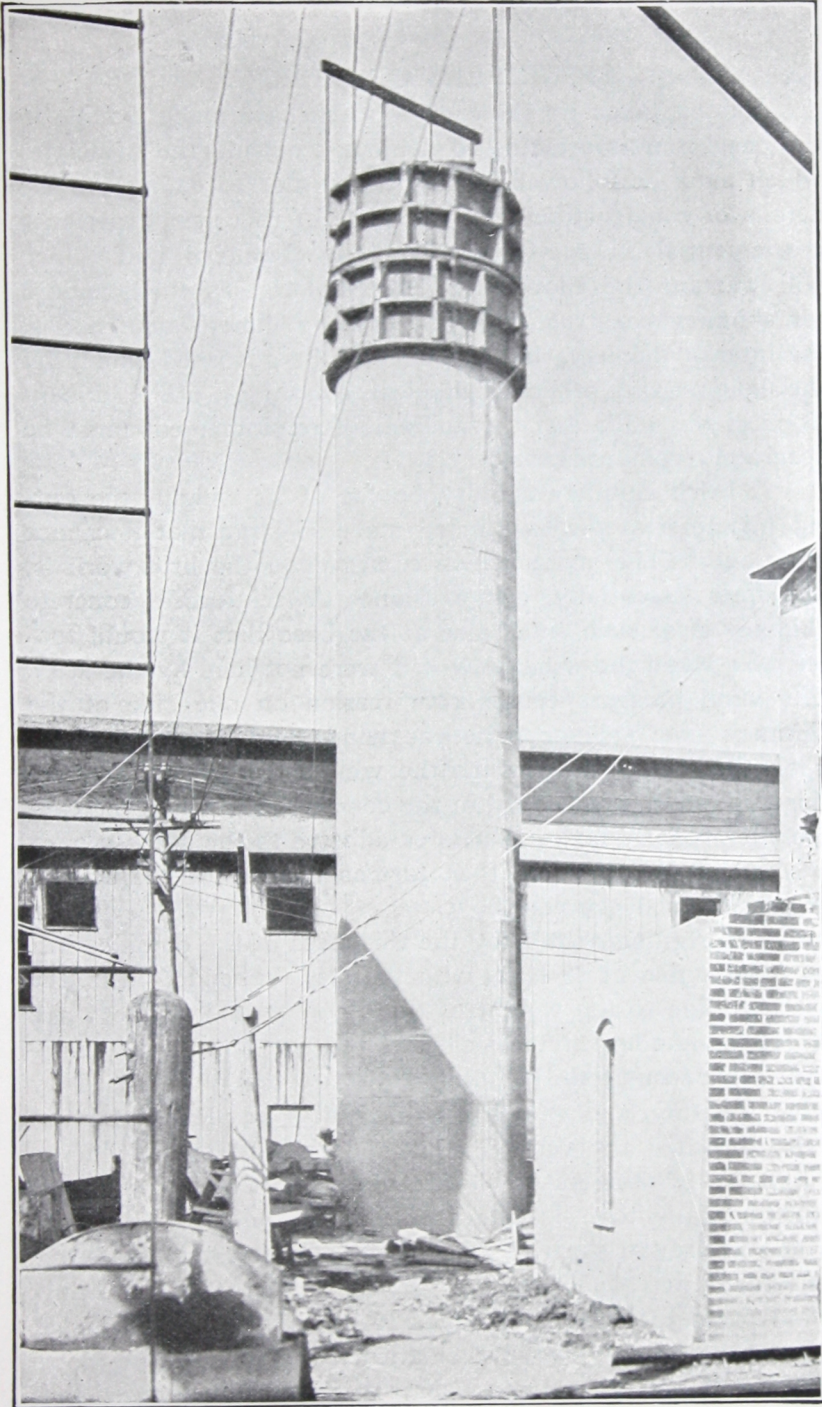


FIG. 9. WILLIAMSPORT CHIMNEY UNDER CONSTRUCTION SHOWING
TAPERING FORMS

(See page 9)

PRINCIPLES OF DESIGN.

Having taken up the causes which have made trouble in the past, it now remains to definitely outline the principles which must be followed in design and also to enumerate the details of construction which in view of this past experience are essential in reinforced concrete chimneys and which will warrant the adoption of this material as the standard for chimney construction. The limiting dimensions, that is, the interior diameter and height must be governed chiefly by the boilers and other mechanical conditions. The dimensions of the walls and the amount of reinforcement must be accurately computed.

A brick chimney stands because of its weight, the outside diameter at the base being made so large that it cannot blow over. The stress which comes upon the brickwork is, therefore, essentially compression. A reinforced concrete chimney is of such small size at the base that it would topple over when the wind blew if it were not held by the steel. The wind pressure causes compression on one side of the chimney (the side opposite the wind) and tension or pull upon the side against which the wind is blowing. To take this pull, steel is imbedded in the concrete, and when the concrete is properly laid, it bonds or adheres to the steel in such a way that they act together, just as they do in the bottom of a reinforced concrete floor.

In designing a chimney the thickness of the outside shell must be sufficient to bear, with the steel imbedded in it, the pressure due to the weight of the chimney and to the wind. A proper number of vertical steel rods or bars must be inserted all around the chimney to resist the pull caused by wind pressure, and steel hoops must also be placed at intervals to stiffen the vertical steel and prevent cracks due to difference in temperature between the interior and exterior, and especially to resist the vertical shear which corresponds to the horizontal shear in a beam. It is customary to assume 50 pounds per square foot of vertical surface as a maximum wind pressure; this corresponds to a wind of 100 miles per hour. It can be proved mathematically that when wind blows against the curved surface, a part of it is ineffective, so that the effective pressure against the chimney is not more than

two-thirds the normal pressure on a vertical plane surface whose width is the diameter of the chimney. Hence, 33 pounds per square foot may be taken for the pressure against this vertical plane. If the chimney is surrounded by buildings, this would of course act only above the roof.

The computation of stresses is by no means a simple calculation because of the combined action of the concrete and steel, which involves the elastic theories. A method given in the 1906 Handbook of the Expanded Metal & Corrugated Bar Company, and which we give in the Appendix to this paper, although somewhat cumbersome for reviewing a chimney already built, offers as good a solution as has yet been given.

In computing the external bending moment on any horizontal plane, account must be taken of all the forces acting up the chimney above this point. If the neutral axis is not at the center of the section, the forces causing bending moment will be the horizontal force due to the wind pressure and the vertical force due to the weight of the chimney above the section. The resultant moment about the neutral axis is therefore a combination of the moments of these two forces, the moment due to the weight being generally negative with respect to the moment due to the wind pressure, and thus reducing the effect of the latter.

As above stated it is customary in chimney design to build an inner shell with an air space of 3 or 4 inches between it and the outer shell. This inner shell is sometimes carried clear to the top of the chimney and in other cases about one-third the distance to the top, the object being both to protect the exterior shell from the high heat of the boilers and provide an insulation which will prevent the lowering of the temperature of the gases which affect the draft.

Concrete chimneys frequently crack at and above the top of the inner shell, so that there is some doubt as to whether this should not be extended higher than the usual one-third. It ought to be possible, however, to so lay and reinforce the concrete as to prevent cracking even with the extremes of outside and inside heat, so that it does not seem advisable at this time to recommend a radical change in the height requirements. The inner shell must be entirely independent of

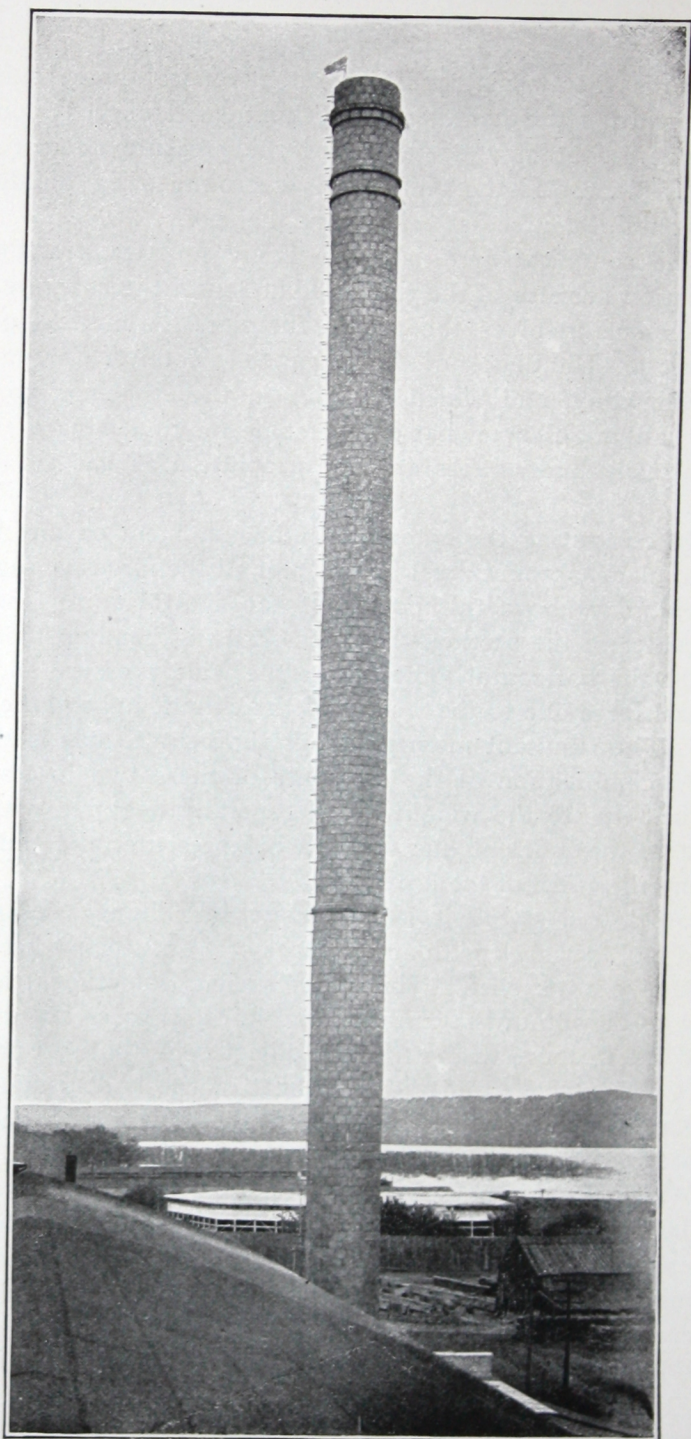


FIG. 10. CHIMNEY OF PEORIA STONE AND MARBLE WORKS CO.

(See page 8)

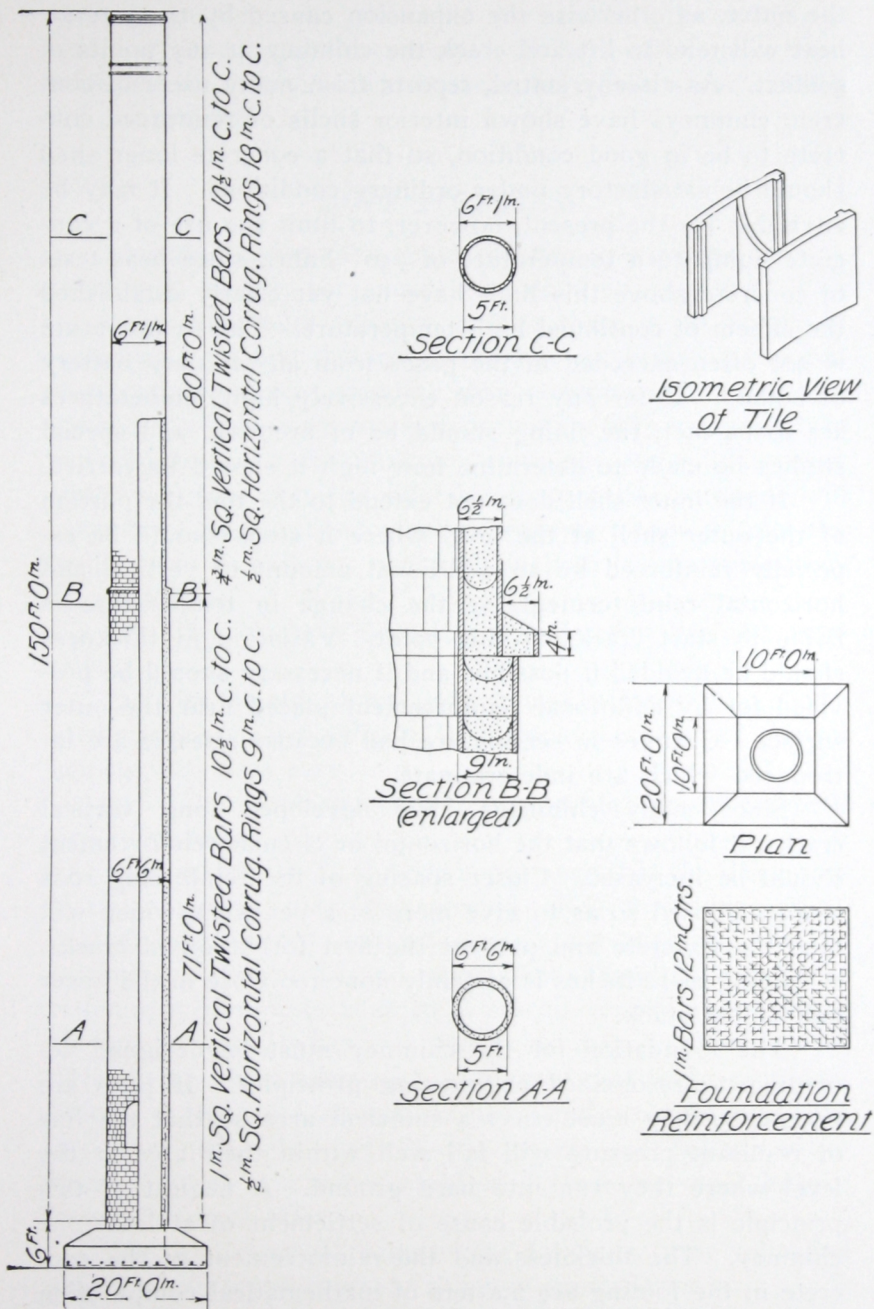


FIG. 11. DESIGN OF PEORIA STONE AND MARBLE WORKS CHIMNEY
(See page 9)

the outer, as otherwise the expansion caused by the interior heat will tend to lift and crack the chimney at any points of contact. As already stated, reports from many users of concrete chimneys have shown interior shells of reinforced concrete to be in good condition, so that a concrete inner shell should be satisfactory under ordinary conditions. It may be advisable for the present, however, to limit the use of a concrete lining to a temperature of 750° Fahr., since heat tests of concrete above this limit have not yet clearly established the effects of continued high temperature. This temperature is not often exceeded in the gases from an ordinary battery of boilers. If for any reason excessively high temperatures are to be met, the lining should be of firebrick, and special studies be made to determine how high it should be carried.

If the inner shell does not extend to the top, the portion of the outer shell at the level where it stops should be especially reinforced by an additional amount of vertical and horizontal reinforcement, as the change in temperature is liable to start cracks at this point. Variation in thickness should be avoided if possible, and if necessary should be provided for by additional reinforcement placed near the outer surface. Changes in section are bad because stresses are introduced which are indeterminate.

Since many chimneys have developed long vertical cracks, it follows that the horizontal or circular reinforcement should be increased. Closer spacing of the reinforcing rods is also advised so as to give more of a net work which will bind the concrete and prevent the first formation of cracks. A spacing of 12 inches is certainly none too close in the lower half of the stack.

The foundation for the chimney must be designed according to recognized engineering principles. If piles are necessary, they must cover a sufficient area so that the line of resultant pressure will fall well within their area at the level where they run into hard ground. A neglect of this principle is the probable cause of settlement of at least one chimney. The thickness and the reinforcement of the concrete in the footing are matters of mathematical computation from the stresses caused by the weight and the wind pressure. In general, we may say that the area must be sufficient to pre-

vent overturning; the allowable pressure on the soil must not be exceeded; and the concrete with its reinforcement must be designed to resist punching shear, horizontal shear, tension and compression.

UNIT STRESSES.

As stated above, it is good practice to compute a chimney for 50 pounds per square foot of wind pressure. This represents maximum velocity, and as there is no danger of exceeding it, at first thought it might seem permissible to employ a smaller factor of safety than is common in other constructions. That is, it would seem that the safe stresses might be taken nearer to the maximum computed stress. However, while it is true that the velocity of 100 miles per hour will never be exceeded, it is for several reasons unsafe to take any greater risk in chimney construction than in other engineering structures.

(1) If a chimney does fall, it endangers life and property.

(2) Its height above ground makes inspection of the workmanship more difficult, and the attainment of perfect homogeneity less easy.

(3) The wind causes vibrations which produce repetition of stresses.

The last reason is of such importance that the discussion of the other two may be neglected. Repeated blows or repeated compressions and pulls upon any material tend to weaken it. Many tests and experiments show that reinforced concrete is admirably adapted to sustain shocks and repeated loadings,—much better, for example, than brickwork,—yet nevertheless these same tests also show that when such conditions or repeated stresses occur, reinforced concrete, like any other materials,—even iron and steel,—will fail at a lower stress than it otherwise would, and therefore must have a larger factor of safety.

The writer would suggest the following unit values as safe for reinforced concrete chimney construction:

Concrete, extreme fibre stress in compression, provided it is capable of attaining a strength of 2,500 lbs. per sq. in. in 28 days.....	600 lbs. per sq. in.
Steel in tension	14,000 lbs. per sq. in.
Concrete in shear	60 lbs. per sq. in.

MATERIALS.

In so important a construction as a chimney, it is necessary that all the materials entering into it shall be of very best quality.

CEMENT. The cement should be such as will satisfy the standard requirements of the American Society for Testing Materials, and the cement actually entering into the chimney should be carefully sampled and tested.

SAND. Sand is not usually tested in concrete work, but it should be tested in the case of any important structure. In a number of concrete failures (not failures of chimneys) which have recently come to the personal knowledge of the writer, the inferior quality of the sand has seriously contributed to the failure. If the sand appears clean and its mechanical analysis or sieve test shows that not more than 30% will pass through a sieve having 40 meshes per linear inch, and if a sand from the same bank has been used in other concrete work which has hardened satisfactorily, it may be accepted without further test, although even then it is advisable to have samples made up in the proportions and with the cement to be used, and tested in a laboratory. If the sand is dirty, or is finer than this, that is, if more than 30% passes a sieve with 40 meshes per inch, a representative sample should be sent to a laboratory and thoroughly tested and either a coarser sand substituted or richer cement proportions than usual adopted. If the sand comes from a bank which has never been used for concrete, it should be submitted to laboratory test notwithstanding its apparent good quality, since it is absolutely impossible to accurately pass upon any sand sample by merely looking at it.

STONE. It has been customary in the past to use a sand mortar for chimneys instead of a true concrete. There is no reason, however, why a clean fine gravel or a fine hard

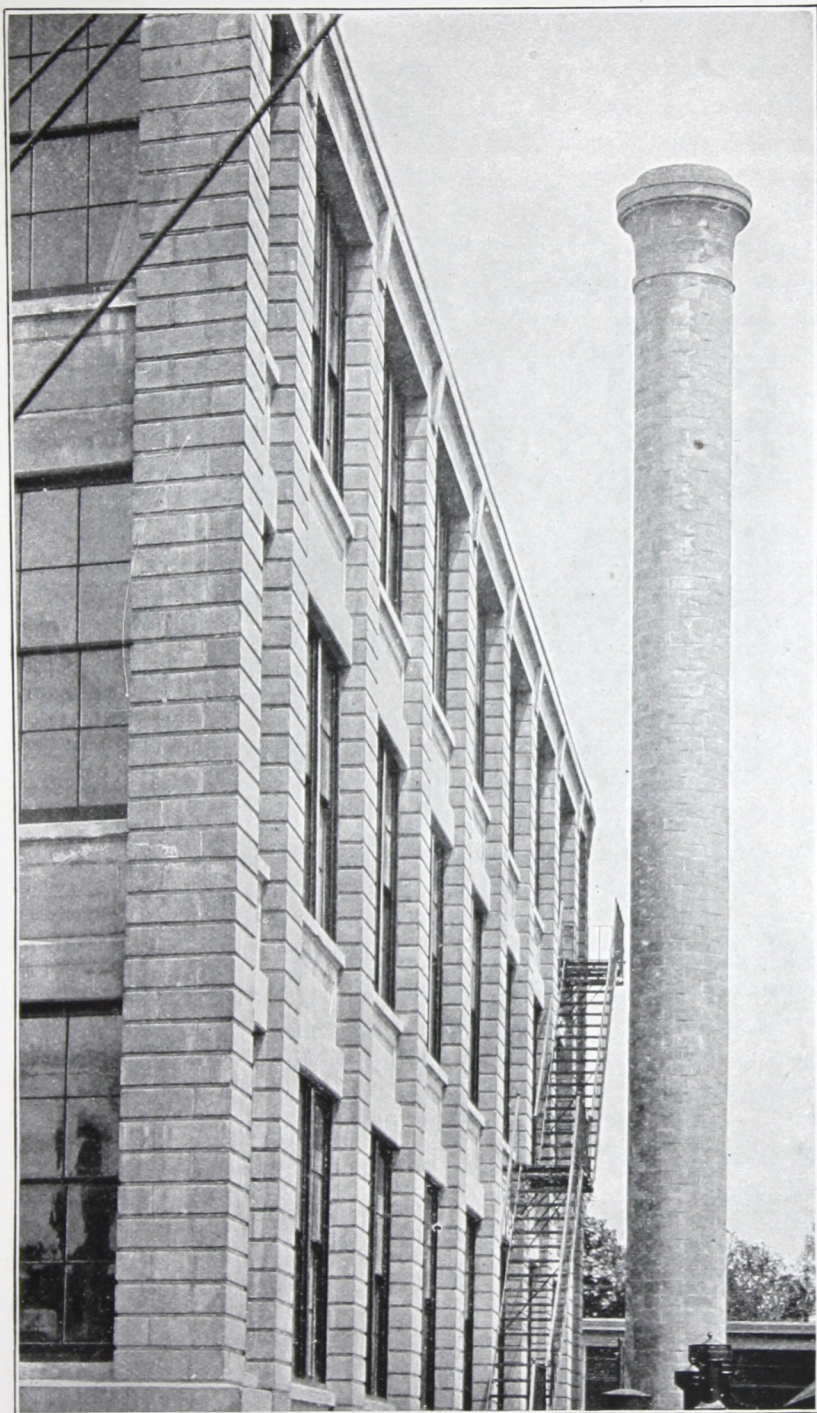


FIG 12. CHIMNEY OF THE SALEM LAUNDRY CO., SALEM, MASS.
(See page 9)



FIG. 13. A PITTSBURG WAREHOUSE WITH CONCRETE CHIMNEY
(See page 9)

crushed stone,—such as trap,—cannot be used with the sand for the outer shell with a reduction in cost, and an increase in density which will make the concrete stronger and less porous. Instead, for example, of using a mortar one part cement to three parts sand, a concrete of one part cement, 2 parts sand and 2 parts $\frac{1}{2}$ -inch stone or gravel will undoubtedly be stronger, denser and more water-tight. Several chimneys have already been built using broken stone as a part of the aggregate. Coarse stone up to $\frac{3}{4}$ inch and 1 inch has sometimes been introduced, but this although producing a stronger mixture, is probably less fire resisting than a finer material.

The concrete has proved suitable for the inner shell as well as the outer, but since mortar is easier to place in a thin wall there is no objection to its use.

WATER. Water used in mixing is customarily required in specifications to be free from acids, alkalies, and vegetable matter. In chimney construction it is equally imperative that the proportion of it shall be gauged exactly right, i. e., more of it used than has been customary, so as to produce a dense mixture with perfect adhesion to the steel.

STEEL. Round and shaped steel bars, such as twisted or corrugated or T-shaped, have been used in chimney construction. Steel with deformed surface gives greater adhesion than the round, but as the round is quite generally adopted in other reinforced concrete construction, it seems safe to use it for chimney construction. T-shaped steel, with its flat surfaces, does not bond so well with the concrete.

Ordinary market steel whose breaking strength in tension is about 60,000 pounds per square inch may be safely used. High carbon steel would give a greater factor of safety, but unless of very high quality—which is difficult to attain without such severe specifications that the cost becomes too large for small structures—high carbon steel is apt to be more brittle and therefore of no advantage. Even with the very best high carbon steel, it is not advisable to allow a pull much greater than 14,000 pounds per square inch, because when this is exceeded there is a possibility of cracks forming in the concrete. It is of course impracticable to make the steel rods long enough to reach the entire height of the chimney. They

have therefore to be lapped, and this lap should be a distance corresponding at least to forty or fifty times the diameter.

CONSTRUCTION.

The principles of reinforced concrete construction which have proved essential in other classes of work, must be followed for chimneys. A disregard of these principles is bound to cause trouble.

First and most essential is the proper proportioning and mixing of the concrete. The measurement of the sand for every bag of cement must be made in an exact measure, and the mixing must be thorough—at least three turnings dry and three wet being required. Special care must be taken in gauging the water. The amount of water to use cannot be expressed in a percentage because different kinds of sand and different brands of cement require different proportions, and furthermore the amount to use to produce the same consistency in the concrete will vary from hour to hour.

It is absolutely wrong, however, to lay any concrete, in which steel is imbedded to take the pull, with what is termed a "very dry" mixture. This dry consistency has been frequently used in chimney construction in the past and appears to be the principal cause of the actual failures and to contribute to a large number of the cracks which have developed in many of the chimneys now standing.

The consistency with which concrete is placed must be wet enough to quake, that is, to form a jelly-like mass; not necessarily wet enough to flow, but with sufficient water so as to insure that in every batch of concrete light tamping will bring the water to the surface. When a very dry mix is used, the water may come to the surface next to the forms, and thus give a good looking concrete, but it will be dry in the center and around the steel where it is most needed. Furthermore, by mixing just on the danger limit, occasional batches will be even dryer than the average so as to permit soft porous places in the concrete.

These statements are not theoretical, but are the result of an actual and extended observation of the results coming from this practice.

With a wet mix, the forms cannot be raised quite so

easily as with a dry mix, and the surface will not be of so uniform a color; nevertheless a wet mix is necessary to produce a dense water-tight concrete and to make it adhere to the steel.

It has been found possible under ordinary weather conditions with a quaking mixture to raise the forms or molds the day after the concrete is placed, but to be on the safe side, two sets of forms may be employed, and raised alternately.

Another objection to dry mixed concrete is the lack of bond between the different layers. Although the stress on



FIG. 14. TYPICAL VIEW OF CRACKED CHIMNEY
(See page 14)

the concrete is chiefly compression so that joints in themselves may not cause failure, they permit cracks to open when the pull comes upon the steel and the water may penetrate to the steel with danger of its rusting. Each batch of concrete should therefore be incorporated with the one below it, and on beginning a day's work, the surface should be thoroughly cleaned and soaked with water, and then a layer of neat cement spread upon it to form a bond between the old and the fresh concrete.

It is essential in the construction that the forms be held absolutely rigid while the concrete is being placed, and until

after it has set. A slight disturbance may form a crack in the interior of the concrete next to the steel so as to scale off later. The steel must be carefully placed, the vertical steel being preferably not far from the center of the wall and the horizontal steel outside of it. In places where special temperature stresses occur, the horizontal steel should be as near as practicable to the stressed surface, although not nearer than $1\frac{1}{2}$ inches. The steel must be well bonded, and the concrete carefully placed and tamped around it, being sure that the concrete next to the steel is actually wet and quaking.

The outside surface must be formed by the molds, no exterior plastering being permissible as this is almost sure to check and scale off with the action of the weather.

The concrete must be laid before the initial set of the cement because regauging retards the set.

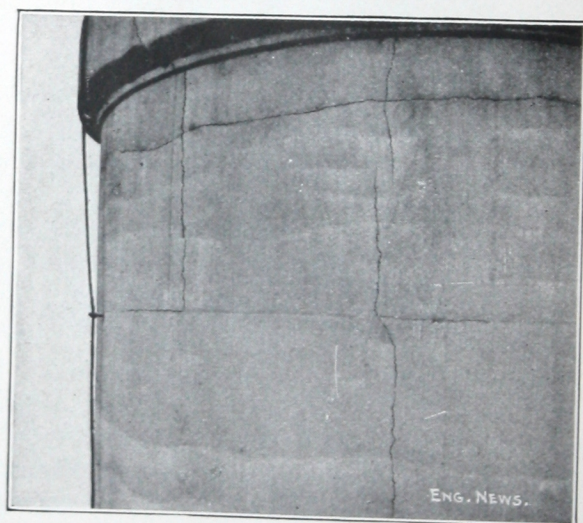


FIG. 15. TYPICAL VIEW OF CRACKED CHIMNEY
(See page 14)

SUMMARY OF ESSENTIALS IN DESIGN AND CONSTRUCTION.

In closing, a recapitulation of the most essential requirements for reinforced concrete chimney design and construction may be made:

(1) Design the foundations according to the best engineering practice.

(2) Compute the dimensions and reinforcement in the chimney with conservative units of stress, providing a factor of safety in the concrete of not less than 4 or 5.

(3) Provide enough vertical steel to take all of the pull without exceeding 14,000, or at most 16,000 pounds per square inch.

(4) Provide enough horizontal, or circular steel to take all the vertical shear and to resist the tendency to expansion due to the interior heat.

(5) Distribute the horizontal steel by numerous small rods in preference to larger rods spaced farther apart.

(6) Specially reinforce sections where the thickness in the wall of the chimney is changed or which are liable to marked changes of temperature.

(7) Select first class materials and thoroughly test them before and during the progress of the work.

(8) Mix the concrete thoroughly and provide enough water to produce a quaking concrete.

(9) Bond the layers of concrete together.

(10) Accurately place the steel.

(11) Place the concrete around the steel carefully, ramming it so thoroughly that it will slush against the steel and adhere at every point.

(12) Keep the forms rigid.

The fulfilment of these requirements will increase the cost of the structure, but if the recommendations are followed, there should be no difficulty in erecting concrete chimneys which will give thorough satisfaction and will endure.

APPENDIX.

FORMULAS FOR USE IN CHIMNEY DESIGN.

The method of analysis presented below for a circular beam was developed by Mr. Alfred E. Lindau, and the formulas are reproduced by permission from the original printing in the 1906 Handbook of the Expanded Metal and Corrugated Bar Company. The notation has been slightly changed to conform to that adopted in Taylor & Thompson's "Concrete, Plain and Reinforced," and an example has been added showing the method of employing the formulas in chimney design. The analysis is not readily adapted to reviewing the design of a chimney, but by the method suggested at the end of the example, it is possible to reach a very close approximation to the actual stresses. The formulas make no allowance for the value of the steel in compression, so that the results obtained will err slightly on the side of safety. The pressure due to the dead weight of the chimney must be allowed for in selecting the unit values of stress.

The common hypotheses are assumed in the analysis, of the invariability of plane sections, tension borne entirely by the steel, absence of initial tension due to setting, and constant modulus of elasticity of concrete within the working limits of the concrete.

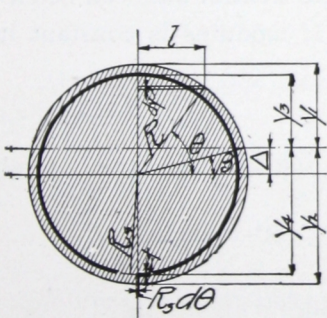


Fig. 1
Section of Beam

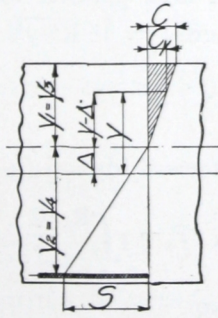


Fig. 2
Stress Diagram

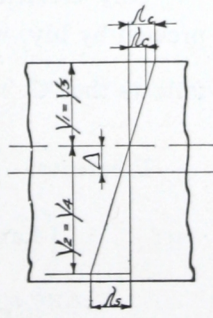


Fig. 3
Deformation Diagram

Let Fig. 1 represent a circular section in which the steel is considered as a continuous shell of thickness t , and the neutral axis is at a distance Δ above the center of the section.

Let R = radial distance to outside of beam.

R_s = radial distance to center of steel reinforcement.

t = thickness of band equivalent to steel reinforcement,

C = unit pressure in extreme fibre of concrete.

S = maximum unit pull or tension in steel.

y_1 = distance from neutral axis to extreme fiber in compression.

$y_2 = 2R - y_1$.

y_4 = distance from neutral axis to maximum stress in steel.

$y_3 = 2R_s - y_4$.

C_y = unit pressure in concrete at any point.

S_y = unit tension in steel at any point.

Δ = distance from center to neutral axis.

θ = arc corresponding to any ordinate y .

β = arc corresponding to ordinate Δ .

$$k = \frac{y_1}{y_2} = \frac{y_1}{2R - y_1}$$

K_a, K_b, K_c, K_d = constants

λ_c^1 = deformation of concrete at extreme fibre.

λ_c = deformation of concrete at any point.

P_c = total force in compression.

P_s = total force in tension.

M_c = moment carried by the concrete in compression.

M_s = moment carried by the steel in tension.

Any elemental area parallel to the neutral axis can be expressed by $l dy$, where $l = \sqrt{R^2 - y^2}$. If modulus is constant it follows that $C_y = C \frac{(y - \Delta)}{y_1}$

Elemental force $= C_y l dy = \frac{C}{y_1} (y - \Delta) (R^2 - y^2)^{\frac{1}{2}} dy$, then total

$$\begin{aligned} \text{force, } P_c &= 2 \int_{\Delta}^R \frac{C}{y_1} (y - \Delta) (R^2 - y^2)^{\frac{1}{2}} dy \\ &= \frac{2C}{y_1} \left[\int_{\Delta}^R y (R^2 - y^2)^{\frac{1}{2}} dy - \Delta \int_{\Delta}^R (R^2 - y^2)^{\frac{1}{2}} dy \right] \end{aligned}$$

Integrating and substituting limits.

$$P_c = \frac{2C}{y_1} \left[\frac{1}{3} (R^2 - \Delta^2)^{\frac{3}{2}} - \frac{\pi R^2}{4} \Delta + \frac{\Delta^2}{2} (R^2 - \Delta^2)^{\frac{1}{2}} + \frac{\Delta R^2}{2} \sin^{-1} \frac{\Delta}{R} \right]$$

If $y_1 = ky_2$ and $y_1 + y_2 = 2R$.

$$\text{Then } y_1 = \frac{2k}{1+k}R, y_2 = \frac{2R}{1+k}, \Delta = \frac{1-k}{1+k}R, k = \frac{R-\Delta}{R+\Delta}$$

By substitution and reduction the total force in compression reduces to

$$P_o = \frac{R^2 C}{k} \left[\frac{8k^{\frac{3}{2}}}{3(1+k)^2} - \frac{\pi}{4}(1-k) + \left(\frac{1-k}{1+k} \right)^2 k^{\frac{1}{2}} + \frac{1-k}{2} \sin^{-1} \left(\frac{1-k}{1+k} \right) \right] \dots (A)$$

As the expression inside the brackets is a constant for any particular value of k , equation (A) reduces to the form

$$P_o = K_a C R^2$$

The moment of this force P_o about the neutral axis can be found by multiplying the elemental area by its lever arm $(y-\Delta)$ and integrating.

Elemental moment

$$dm_o = C_y l dy (y-\Delta) = \frac{C}{y_1} (y-\Delta)^2 (R^2 - y^2)^{\frac{1}{2}} dy$$

By expansion

$$M_o = \frac{2C}{y_1} \left[\int_{\Delta}^R y^2 (R^2 - y^2)^{\frac{1}{2}} dy - 2\Delta \int_{\Delta}^R y (R^2 - y^2)^{\frac{1}{2}} dy + \Delta^2 \int_{\Delta}^R (R^2 - y^2)^{\frac{1}{2}} dy \right]$$

Integrating and substituting limits

$$M_o = \frac{2C}{y_1} \left[\left(\frac{R^2}{4} + \Delta^2 \right) \left(\frac{\pi R^2}{4} - \frac{R^2}{2} \sin^{-1} \frac{\Delta}{R} \right) - \Delta (R^2 - \Delta^2)^{\frac{1}{2}} \left(\frac{2\Delta^2 + 1}{24} 3R^2 \right) \right]$$

Substituting

$$y_1 = \frac{2k}{1+k}R, \Delta = \left(\frac{1-k}{1+k} \right) R$$

We have for the value of the moment of the force P_o about the neutral axis

$$M_o = \frac{R^3 C}{k(1+k)} \left[\frac{5-6k+5k^2}{4} \left(\frac{\pi}{4} - \frac{1}{2} \sin^{-1} \frac{(1-k)}{(1+k)} \right) - \frac{(1-k)k^{\frac{1}{2}}}{12(1+k)^{\frac{3}{2}}} (15+22k+15k^2) \right] \dots (B)$$

Which for a definite value of k reduces to the form

$$M_o = K_b C R^3$$

To find similar expressions for the steel, it will be found convenient to express the area element by $tR_s d\theta$. Referring again to the figure

$$y = R \sin \theta, \text{ and } C_y = \frac{(y+\Delta)}{y_s} S$$

$$\text{Element of force} = \left(\frac{y + \Delta}{y_4} \right) \text{StR}_s d\theta$$

Total force

$$P_s = \frac{2\text{StR}_s}{y_4} \int_{-\beta}^{\frac{\pi}{2}} (R_s \sin \theta + \Delta) d\theta$$

Integrating and substituting limits

$$P_s = \frac{2\text{StR}_s}{y_4} \left[R_s \cos \beta + \Delta \left(\frac{\pi}{2} + \beta \right) \right]$$

$$\Delta = \frac{1-k}{1+k} R_s, \quad y_2 = \frac{2}{1+k} R_s, \quad \cos \beta = \frac{2k^{1/2}}{1+k}$$

from which it follows that the total force of tension in the steel is

$$P_s = \text{StR}_s \left[2k^{1/2} + (1-k) \left(\frac{\pi}{2} + \sin^{-1} \frac{(1-k)}{(1+k)} \right) \right] \dots \dots \dots (C)$$

$$\text{or, } P_s = K_c \text{StR}_s$$

To find the moment, multiply element of force by its distance from neutral axis ($y + \Delta$), and integrate

$$dm_s = S \frac{(y + \Delta)^2}{y_4} t R_s d\theta$$

$$M_s = 2 \int_{-\beta}^{\frac{\pi}{2}} \frac{(y + \Delta)^2}{y_4} \text{StR}_s d\theta$$

Integrating and substituting limits

$$M_s = \frac{2\text{StR}_s}{y_4} \left[\left(\frac{\pi}{4} + \frac{\beta}{2} - \frac{\sin 2\beta}{4} \right) R_s^2 + 2\Delta R_s \cos \beta + \Delta^2 \left(\frac{\pi}{2} + \beta \right) \right]$$

Substituting for Δ and collecting terms

$$M_s = \frac{\text{StR}_s^2}{(1+k)} \left[\left(\frac{\pi}{2} + \sin^{-1} \frac{(1-k)}{(1+k)} \right) \left(\frac{3-2k+3k^2}{2} \right) + 3k^{1/2}(1-k) \right] \dots \dots (D)$$

which for any given value of k reduces to the form

$$M_s = K_d \text{StR}_s^2$$

Assigning values to C and S will determine the resisting moment, since $\frac{y_1}{y_4} = \frac{\lambda_v^1}{\lambda_s}$ will locate the neutral axis and equating P_o to P_s will determine the thickness t of the steel shell or the percentage of the reinforcement. The resisting moment is the sum of M_o and M_s for the proper values of k .

TABLE OF CONSTANTS

FOR EQUATIONS A, B, C, AND D, FOR VARIOUS VALUES OF k

k	K_a	K_b	K_c	K_d
.10	.0573	.0060	2.9086	4.0295
.15	.0976	.0146	2.8168	3.7575
.20	.1398	.0269	2.7348	3.5017
.25	.1824	.0421	2.6607	3.2804
.30	.2244	.0600	2.5930	3.0818
.35	.2653	.0798	2.5308	2.9027
.40	.3050	.1011	2.4732	2.7406
.45	.3431	.1238	2.4196	2.5931
.50	.3797	.1474	2.3695	2.4585
.55	.4147	.1716	2.3227	2.3353
.60	.4482	.1958	2.2786	2.2221
.70	.5106	.2461	2.1978	2.0214
.80	.5675	.2959	2.1253	1.8494
.90	.6193	.3449	2.0597	1.7006
1.00	.6667	.3927	2.0000	1.5708

Example—What is the resisting moment and the corresponding steel reinforcement required at the base of a chimney whose outside diameter is 10 feet and thickness of shell 9 inches, if, after allowing for weight of chimney, maximum allowable fiber pressure in concrete, C , is 600 pounds, and maximum allowable fiber pull in steel is 14,000 pounds per square inch?

Solution—Assuming the modulus of steel as 30,000,000 and that of the concrete as 2,000,000, we have

$$\frac{y_1}{y_2} = \frac{\lambda_c^1}{\lambda_s} = \frac{600 \times 30,000,000}{2,000,000 \times 14,000} = .643$$

$$\frac{y_1}{y_2} = \frac{R - \Delta}{R_s + \Delta} \text{ or } \Delta = \frac{R - .643 R_s}{1 + .643}$$

R_1 the radial distance to outside of shell = 60 inches.

R_2 the radial distance to inside of shell = 51 inches.

R_s (assuming centre of steel 3" from outside) = 57 inches.